Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/AU05/000406

International filing date: 21 March 2005 (21.03.2005)

Document type: Certified copy of priority document

Document details: Country/Office: AU
Number: 2004901438
Filing date: 19 March 2004 (19.03.2004)

Date of receipt at the International Bureau: 12 April 2005 (12.04.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

PCT/AU2005/000406

Australian Government

Patent Office
Canberra

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Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant:

JRB ENGINEERING PTY LTD

Invention Title:

OPTICAL METHOD OF DETERMINING A PHYSICAL ATTRIBUTE OF A MOVING OBJECT

The invention is described in the following statement:

Optical Method of Determining a Physical Attribute of a Moving Object

Field of the Invention

The present invention relates to an optical method for determining a physical attribute of a moving object.

Background of the Invention

A number of optical methods and systems are readily available for determining the physical attribute of an object such as the dimension of an object or its orientation. In particular, there exists a number of dynamic measuring systems based on the combination of fanned laser beams and digital cameras. A fanned laser beam emits a fan of laser rays which all lie in a common plane emanating from a centre of the laser. When the fanned laser illuminates a body it is seen as a line that defines the intersection between the laser plane and an outer surface of the body. If the line created by the fanned laser is recorded by a digital camera, and the fanned laser and digital camera are in a fixed position relative to each other, then it can be shown mathematically that each point in the camera's view illuminated by the laser can be resolved into a three dimensional position in any particular co-ordinates so long as the orientation of the laser plane, and the position and orientation of the camera are predefined precisely in co-ordinates related to the body being observed, and provided the camera's optical settings and characteristics are also known.

In industrial applications setting the lasers and cameras into precisely known orientations relative to the body being measured is difficult and sometimes impractical.

Summary of the Invention

It is an object of the present invention to provide an optical method for determining a physical attribute of an object utilising fanned lasers and digital cameras which does not require precise mechanical get-p of the three dimensional location and orientation of the fanned lasers and digital cameras relative to the moving object.

According to the present invention there is provided an optical method for determining the physical attribute of an object moving along a defined path said method comprising:

fixing at least one fanned laser at a position outside of said path to project its laser beam onto said moving object when said moving object is at a trigger location;

fixing at least one camera at a location to view said moving object when illuminated by said laser beam at said trigger location, each camera producing a digital image comprising an array of pixels;

forming a calibration block comprising two planar surfaces which intersect in a line forming an edge of said block and, at least three non-colinear visible points on each of said planar surfaces at known locations said calibration block defining a calibration co-ordinate system;

temporarily mounting said calibration block in said path in view of said at least one camera, and where illuminated by said at least one fanned laser;

producing an image of said block on each camera and determining for each of one or more pixels of said image an equation in terms of said calibration co-ordinate system, of a ray passing through a centre of lens of said

camera which, when projected onto said block coincides with said pixel;

determining an equation of a plane in said calibration co-ordinate system containing said fanned laser beam;

removing said calibration block;

taking an image of said object when illuminated by said at least one laser beam at said trigger location and utilising said laser plane equations, determining a three dimensional location in said calibration co-ordinate system of selected pixels of said object illuminated by said at least one laser, and from said three dimensional locations determining physical attribute of said object.

Preferably forming said calibration block comprises providing each of said planar surfaces with at least three visible points at random or pseudo-random locations.

Preferably forming said calibration block further comprises arranging said first and second planar surfaces at right angles to each other.

Preferably forming said calibration block further comprises providing a third planar surface having a first edge coincident with an edge of said first planar surface distant said second planar surface, and a fourth planar surface having a first edge coincident with an edge of said third planar surface distant said first planar surface, and a second edge coincident with an edge of said second planar surface distant said first planar surface.

Preferably said second and third planar surfaces are parallel to each other and said first and fourth planar surfaces are parallel to each other.

Preferably fixing said at least one fanned laser comprises fixing two or more fanned lasers at respective locations outside of said path whereby the laser beams from each laser projects onto said moving object at different locations.

Brief Description of the Drawings

An embodiment of the present invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a perspective view from the side of a pantograph on the roof of an electrically powered train;

Figure 2 is a perspective view from the front of a pantograph head;

Figure 3 is a view of Section AA of the pantograph head depicted in Figure 2;

Figure 4 illustrates an optical measurement system incorporating an embodiment of the present method;

Figure 5 is an enlarged view of the system shown in Figure 4 from the perspective of one camera incorporated in the system;

Figure 6 is a view of a pantograph head illuminated by a plurality of fanned lasers incorporated in the system shown in Figures 4 and 5;

Figure 7 is a cross-sectional view of a portion of the pantograph head as viewed by a camera in the system depicted in Figures 4 and 5;

Figure 8 is a schematic representation of a portion of the calibration block incorporated in an embodiment of the present method;

Figure 9 is an illustration of the measurement system during a calibration process;

Figure 10 is a photograph of the calibration block incorporated in the present invention when viewed from one of the cameras in the system depicted in Figures 4 and 5;

Figure 11 is a photograph of the calibration block when viewed from another of the cameras incorporated in the system shown in Figures 4 and 5 and illuminated by a plurality of fanned lasers;

Figure 12 illustrates the co-ordinate systems of major components of the system illustrated in Figures 4 and 5;

Figure 13 illustrates the relationship between the co-ordinate systems of an image plane of a camera incorporated in the system, the camera, and the calibration block;

Figure 14 illustrates a fanned laser illuminating the calibration block;

Figure 15 illustrates the orientation of the pantograph head;

Figure 16 is a representation of a portion of the pantograph as seen by one of the cameras in the system shown in Figures 4 and 5;

Figure 17 is a schematic representation of a method for fitting a cylinder profile to the pantograph head;

Figure 18 depicts various planes on the pantograph carbon and carrier;

Figures 19a and 19b illustrate the geometry in the process of fitting a cylinder to the pantograph head; and,

Figure 20 illustrates the geometry in measuring the thickness or height of the pantograph carbon.

Detailed Description of Preferred Embodiment

An embodiment of the present method is described in relation to a pantograph of an electrically powered train. With particular reference to Figures 1-3, the pantograph head 10 comprises two or more parallel and spaced apart metal beams 12a and 12b (hereinafter referred to in general as "beams 12"). The beams 12a and 12b comprise respective metal sections 13a and 13b (hereinafter referred to in general as "metal sections 13") and attached carbon bushes 14a and 14b (hereinafter referred to in general as "carbons 14"). The metal sections 13 together are known as the "carrier" The beams 12 and carbons 14 extend transverse to an overhead wire 16 from which the train derives electric current for powering its engines. The pantograph and wire 16 are generally orientated so that the wire contacts the carbons 14 in a region about their mid-point. The carbons 14 have a central portion 18 which comprises the majority of its length and is of uniform thickness h, and contiguous end portions 20 which reduce in thickness. In use, the wire 16 is substantially always maintained in contact with the central portion 18 of the carbons 14.

Over time, the carbons 14 wear from contact with the wire 16, and occasionally are damaged through contact with foreign objects. The wear is reflected through a decrease in the thickness h of the carbons 14. Damage through

contact with foreign objects is reflected in the removal of chunks of material from the carbons 14.

Embodiments of the present invention provide for an optical system and method for determining a physical attribute of a moving object, in the present embodiment the moving object being the pantograph 10 or more particularly the carbons 14 and the physical attribute being the thickness h of the carbons 14 along their length, without requiring precise mechanical set-up of various elements of an associated optical measurement system 22.

Figure 4 depicts the general set-up of the optical system 22. The system comprises three fanned lasers 24a, 24b and 24c (hereinafter referred to in general as "lasers 24") which are supported at a vertical distance h1 above the wire 16; and, two digital cameras 26a and 26b (hereinafter referred to in general as "cameras 26") which are located a vertical distance h2 below the wire 16 on either side of the pantograph head 10. Each of the lasers 24a-24c produces a corresponding laser plane 28a-28c (hereinafter referred to in general as "laser plane 28), being a plane of laser rays emitted from that particular laser 24. The lasers 24 emit radiation of a visible wavelength and thus when the laser planes 28 project onto or illuminate the pantograph 10 they each produce two visible laser stripes. The laser 24a produces laser stripes 32a and 32b on beams 12a and 12b respectively, laser 24b produces laser stripes 34a and 34b on beams 12a and 12b respectively, and laser 24c produces laser stripes 36a and 36b on beams 12a and 12b respectively.

Each of the cameras 26 looks upwardly at the pantograph head 10 toward backboards 38a and 38b respectively which are supported above the wire 16. The camera 26a views the stripes 32a,32b,34a and 34b, while the camera 26b views

the stripes 34a,34b,36a and 36b. The backboards 38a and 38b allow the cameras 26 to record a silhouette of the pantograph head 10, and in particular the carbons 14.

The lasers 24, cameras 26 and backboards 38 are all supported in locations outside of the path of motion of the pantograph 10 and the train to which it is coupled.

In addition the lasers 24 and camera 26 are arranged so that the laser planes are not parallel to the image plane of the cameras nor passes through the camera origin. Preferably the laser planes are about 45° to image plane.

The system 22 views the front of the pantograph 10 relative to its direction of motion. A second identical system may also be provided to view the opposite or reverse side of the pantograph head 10. This will enable measurement of the carbons 14 from opposite sides.

The following description is made in relation to only one of the cameras 26a of the system 22 as the operation of the system 22 and the associated method is identical for the camera 26b and indeed for corresponding cameras in an identical system (not shown) viewing the rear side of the pantograph head 10.

Figure 6 depicts the view of the pantograph head 10 from camera 26a when illuminated by the lasers 24a and 24b. The camera 26a is able to see, against the backboard 38a, laser stripes 32a and 32b, 34a and 34b and 36b. However the capture of the image of stripe 36b is not critical.

Figure 7 depicts in cross-section the beam 12a at a location illuminated by the laser 24a. The laser 24a produces the stripe 32a which is depicted in heavier line. This stripe extends across an upper surface 40 of the carbon 14a down a front surface 42 of the carbon 14a,

along an upper surface 44 of the metal section 13a and down a front surface 46 of the metal section 13a terminating at a lowest point 48. The lowest point 48 coincides with leading or front bottom corner of the metal section 13a. The beam 12a as viewed by the camera 26a has a silhouette of a width W. However, the true height or thickness of the entire beam 12a is height H. The height H, is a combination of the thickness of the metal section 13a which remains constant throughout the life of the pantograph head 10, and the thickness h of the carbon 14a which decreases in time due to wear.

Knowing the location in three dimensions of the equivalent corner point 48 for each of the laser stripes 32a,32b,34a and 34b gives four points on the surface of the pantograph head 10. From these points, the orientation of the pantograph head can be determined. Further, from the knowledge of the orientation of the pantograph head 10, relative to the camera 26a, a transformation between the silhouette width W and the height H can be derived and thus the thickness h of the carbon 14 determined.

As mentioned in the Background of the Invention, it is possible to determine the three dimensional location of a point illuminated by a laser if the position of the laser and position and direction of the camera are precisely defined relative to the body being observed. However, it will be appreciated that determining these positions particularly having regard to the lasers and cameras being located off the ground, precise measurement is impractical.

Embodiments of the present invention enable such a relationship to be determined without the need to physically measure with precision the location and orientations of the lasers 24, cameras 26 and pantograph head 10. Rather, the present method utilises a

calibration process and calibration block to determine the relative orientations of the camera 26 and laser planes 28.

The calibration block 50 (see Figures 8-11) comprises a minimum of two planar non-parallel surfaces, 52 and 54 each composed of corresponding precise rectangular plates which intersect at a line or edge 56. Ideally, although not necessarily, the surfaces 52 and 54 are at right angles to each other. An edge 58 of the surface 52, and adjacent edge 60 of the surface 54, together with the edge 56 are machined to create a precise set of rectangular axes with a vertex at a corner 0. Each of the surfaces 52 and 54 of the calibration block 50 is provided with at least three markings in the form of dots 62 created by drilling corresponding small holes (of approximately 5mm diameter) through the plates which are filled with translucent material of visually contrasting colour to the surfaces 52 and 54 (for example the surfaces may be black in colour and the translucent material white). To highlight the markings 62 the block 50 is backlit from the rear. The dots 62 are positioned at random or pseudo-random locations on their respective surfaces. However the location of each dot on surface 52 is precisely known relative to edges 56 and 58, while the dots 62 on the surface 54 are precisely known relative to the edges 56 and 60. The location of the dots 62 is held in a look up table on a computer.

In the event that the system 22 is to be used to measure the characteristics of the pantograph from both the front and the rear, the block 50 will comprise two further surfaces (not shown) of identical configuration to the surfaces 52 and 54 and attached to the surfaces 52 and 54 to form a box-like structure comprising the surface 52, the surface 54 a further surface parallel to the surface 52 and a further surface parallel to the surface 54.

In order to calibrate the system 22, the calibration block 50 is temporarily supported at a location corresponding generally to a location through which the pantograph head 10 will pass. The calibration block must stationery, in the field of view of all cameras, and in a position where all lasers shine across its faces. Theoretically it is possible to set the calibration block 50 at any orientation relative to the local world co-ordinates. The orientation of the pantograph head 10 can be computed in the local world co-ordinates so long as it is possible to compute the transformation from the calibration block orientation to the natural world co-ordinates. However this process is simplified by orientating the calibration block 50 during the calibration process so that its axes are essentially aligned with the rails as follows.

Referring to Figure 9, the calibration 50 is orientated so that it is set in essentially the same location (the trigger location) of the pantograph head 10 when the pantograph head 10 is being measured. This places the calibration block 50 in the path of the laser planes 28 and in view of the cameras 26. The physical location of the block does not need to be precise, so long as it is in the field of view of the camera and is illuminated by the lasers. A mechanical frame (not shown) supports the calibration block 50 in a location so that the surfaces 52 and 54 are approximately at 45° to the horizontal, an upper edge 64 of the calibration block 50 contacts the wire 16 and the edge 56 of the calibration block 50 lies square to the rails.

Figure 10 shows an actual calibration block 50 from the position of camera 26a prior to illumination by the lasers 24. The dots 62 are clearly visible in an image plane of the camera 26a.

Figure 11 depicts the view of the calibration view 50 from the camera 26b when illuminated by lasers 24b and 24c and showing corresponding laser stripes 66b and 66c. The laser 24a also produces a visible stripe 66a on the calibration block 50 which is in the field of view of camera 26a.

The calibration of the system, which enables the location of the lasers 24 and cameras 26 to be determined in a calibration co-ordinate system corresponding to the co-ordinate system of the block 50 is described below. The origin O of this co-ordinate system is in the middle of the block.

Broadly speaking the method of calibration provides the position and orientation of the cameras relative to the co-ordinates defined by the calibration block 50, and equations of the laser planes 28 in the calibration co-ordination system. From this the three dimensional location of any point illuminated by a laser stripe on the pantograph (or any other object) when viewed by one of the cameras can be determined. With a three dimensional location of these points known, the orientation of the pantograph and any desirable physical characteristic thereof can be calculated.

Each laser 26 emits a corresponding plane of light, ie laser planes 28. The equation of any one of these planes can be expressed in vector form by the equation

$$\mathbf{n}.\mathbf{w} = c \qquad \text{equation 1}$$

where $\mathbf{n}$ is the unit normal to the plane, $\mathbf{w}$ is a point on the plane and c is a constant equal to the distance from the origin O of the calibration block.

The orientation of the laser plane is entirely arbitrary; however it is practical to align it as close as possible to be vertical.

The image produced by each camera 26 is a regular two dimensional rectangular array of pixels.

A given pixel position (p_x,p_y) in the image relates to a single ray in 3D defined by the camera co-ordinate mapping transformation (i.e. camera orientation). This ray will intersect a laser plane 28 in a unique point in 3D. Hence if the mathematical relationship of the laser plane and the rays from the camera can be defined then the 3D position of any point illuminated by the laser can be computed from its corresponding pixel co-ordinates. This is true for all points on the stripes 32a, 32b, 34a, 34b, 36a and 36b traced on the pantograph.

In this analysis it is assumed that the lasers 26 and cameras 24 can be positioned fairly accurately, but not with enough precision to allow a hard-coded transformation between the camera image and the laser position. This transformation is determined by calibration. The accuracy of this system depends on the calibration process rather than the physical camera and laser setup.

Calibration is used to define the relationship between the 3D co-ordinate system used (calibration block co-ordinates) and the 2D image co-ordinates.

The system 22 incorporates five co-ordinate systems as shown in Figure 12; namely:

Image co-ordinate system: This defines the location of each pixel on the image plane of the camera 26 producing

the image. The image plane is parallel to the lens (camera co-ordinate x-y plane).

Camera co-ordinate system: This is the co-ordinate system of a camera 26 with the origin at the centre of its lens and the z-axis directly through the centre of the lens and normal to the lens.

Calibration co-ordinate system: The co-ordinate system defined from the calibration process using the calibration block. The axes should align as close as possible with the local world co-ordinate system. When front and rear images are to be used, there are two calibration co-ordinate systems - one for the front cameras and the other for the rear cameras.

Pantograph co-ordinate system: The co-ordinate system defined square to the pantograph, with the origin in the centre of the pantograph.

Local world co-ordinate system: The absolute co-ordinate reference system, with one axis vertical one axis parallel, and the other square to the rails on which the train carrying the pantograph travels.

Figure 13 shows the relationship between the following three co-ordinate systems:

Calibration (3D) co-ordinate system ($\underline{w}$).

Camera co-ordinate system ($\underline{c}$).

Image (2D) co-ordinate system ($\underline{p}$).

The image co-ordinates are related to the camera co-ordinates by:

$$p_x = \frac{c_x}{c_z} = Tan(\theta_y) \quad \Rightarrow \quad c_x - p_x c_z = 0 \qquad \text{(Eqn 2)}$$

$$p_y = \frac{c_y}{c_z} = Tan(\theta_x) \quad \Rightarrow \quad c_y - p_y c_z = 0 \qquad \text{(Eqn 3)}$$

The c_z term is the perspective scaling factor.

The calibration co-ordinates are related to the camera co-ordinates by:

$$\begin{bmatrix} c_x \\ c_y \\ c_z \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} w_x \\ w_y \\ w_z \\ 1 \end{bmatrix} \quad (ie\ \underline{c} = H \cdot \underline{w}) \qquad \text{(Eqn 4)}$$

The terms h_{11} to h_{33} define rotation and h_{14}, h_{24}, h_{34} define translation. If the z-origins of the two co-ordinate systems do not coincide ($h_{34} \neq 0$) then the entire system can be divided by h_{34} to reduce the number of unknowns. This has no effect on p_x and p_y as the numerator and denominators in [Equation 1] and [Equation 2] have both been divided by h_{34}. Therefore the term h_{34} is now 1. Independent scaling of the pixel co-ordinates is incorporated in H.

Expanding [Equation 4] and substituting into [Equation 2] and [Equation 3]:

$$\begin{bmatrix} w_x & w_y & w_z & 1 & 0 & 0 & 0 & 0 & -p_x w_x & -p_x w_y & -p_x w_z \\ 0 & 0 & 0 & 0 & w_x & w_y & w_z & 1 & -p_y w_x & -p_y w_y & -p_y w_z \end{bmatrix} \cdot \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{14} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{24} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix} = \begin{bmatrix} p_x \\ p_y \end{bmatrix} \qquad \text{(Eqn 5)}$$

The two sets of equations have eleven unknowns, therefore at least six points are required, more can be used to apply a least squares fit. All the points should not be collinear and arranged on at least two orthogonal planes.

The inverse of H (H^{-1}) defines the transformation from camera co-ordinates to calibration co-ordinates.

All points pass through the camera origin in the centre of the lens: $\underline{c}_0 = (0, 0, 0, 1)^T$. In calibration co-ordinates: $\underline{w}_0 = H^{-1}\ \underline{c}_0$.

On the camera plane $c_z = 1$ the image co-ordinates $\underline{p} = (p_x, p_y)$ correspond to $\underline{c}_1 = (p_x, p_y, 1, 1)^T$. In calibration co-ordinates: $\underline{w}_1 = H^{-1}\ \underline{c}_1$.

Each point in the image corresponds to a ray extending from the centre of the lens:

$$\underline{w}(t) = \underline{w}_0 + t \cdot (\underline{w}_1 - \underline{w}_0) \quad [t \geq 0] \qquad \text{(Eqn 6)}$$

Any plane normal to the camera's z-axis can be used rather than the camera plane $C_z = 1$ - it only rescales the parametric variable.

If the plane the point lies in is known then the calibration co-ordinate can be determined from the image co-ordinate by the intersection of the ray and the plane ($\underline{n} \cdot \underline{w} = d$) as long as the ray and plane are not parallel:

$$t = \frac{d - \underline{n} \cdot \underline{w}_0}{\underline{n} \cdot (\underline{w}_1 - \underline{w}_0)} \qquad \text{(Eqn 7)}$$

During the calibration process both planes 52 and 54 of the calibration block 50 must be visible by the associated cameras 26 and the laser planes 28 must also strike both surfaces. The following process will calibrate the system:

Move the block 50 to a known position with respect to a global reference (e.g. trigger point). The block 50 should be square to the rails and in the expected location of the pantograph head 10.

Use the dots 62 to determine the transformation matrices for all cameras 26. The lasers 24 must be off at this

stage if they are so bright that they interfere with the process of locating the dots. A second image must then be taken with the lasers turned on (the block must remain stationary).

Use the stripes 66 (see Figure 9) traced by the lasers 24 on the block's planes 52,54 to determine the laser's planes 28. Three points (not collinear) are required to define each plane ($ax+by+cz=1$), more can be used for a least squares fit:

$$\begin{bmatrix} a & b & c \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 \end{bmatrix} \qquad \text{(Eqn 8)}$$

The three points may be for example for laser plane 28a, two points on the portion of stripe 66a on surface 52 and one point on the portion of stripe 66a on surface 54.

The transformation process uses the information determined by the calibration to calculate the co-ordinates of the pantograph seen in the image. Figure 15 defines the pantograph's orientation in the system 22 which measures the carbons 14 from the front and back of the pantograph head 10. This Figure depicts lasers 24d, 24e and 24f for illuminating the back of the pantograph head 10. The following process describes how to measure the carbons 14 on the outside of the near beam 12a and the inside of the far beam 12b.

Locate the two laser stripes in each image on the carrier (the LHS and RHS images will share the middle stripe). Each laser stripe will form two lines - one along the side of the carbon 14 and the other along the side of its corresponding metal section 13. The two lines will not be parallel and may be discontinuous as shown in Figure 16 due to the laser position, shape and the camera angle.

The image of the pantograph is taken as the train moves past. A triggering mechanism, (either mechanical, electro-magnetic or optical) sense when the pantograph is in the correct position for the cameras to take an image.

The lowest endpoint of each stripe across the metal section 13 provides a known point on the bottom of the near side of the beam 12. Two pairs of such points on the near and far beams 12a and 12b allow a cylinder [Figure 17] to be fitted to match the curvature of the beams 12. In this regard it should be noted that the beams 12 are not straight but are manufactured with a curvature, typically of a radius of about 10 metres. However this may vary for different suppliers. Moreover the beans could be flat. The present method is applicable to all possible configurations but is described in relation to curved beams.

The cylinders axis is normal to the pantograph's *x-z* plane. The orientation of the cylinder's axis gives the pitch and yaw (relative to the calibration co-ordinate system).

Three planes (normal to the cylinders axis) can be defined based upon the pantograph's profile as shown in Figure 18, using a fixed offset from the bottom of the near side of a beam 12.

Carbon plane: Along the near face of the carbon, this will allow the 3D co-ordinates of the top near edge, C_i of the carbon to be determined from the silhouette.

Carrier plane: Along the far edge of the underside of the carrier, this will allow the 3D co-ordinates of the bottom far edge b_i of the beam 12 (ie metal section 13) to be determined from the silhouette.

Feature plane: Along the underside of the carrier 12, aligned with a feature point, this will allow the location

of features to be determined. A feature point is any known point which would appear in the silhouette. For example it may be the location of a bolt passing through the metal section 13.

The co-ordinates along the top and bottom of the silhouette will allow the height of the carbon to be determined.

A circle is fitted to the carrier points in the carrier plane to determine the location of the centre of this circle. The roll is determined by the relative position of their centre of this circle relation to the mid point of the currier.

Matching known features from the feature plane on the bottom edge of the carrier will allow the position of the pantograph to be determined from its profile (in calibration co-ordinates), and the mid point of the carrier to be determined.

Data from the left and right side images are combined to form a complete profile of the pantograph.

The carbons 14 and metal sections 13 of the pantograph head are generally curved with a constant radius when viewed along the direction of the overhead wire. It is therefore possible to fit a section of a cylinder of known radius (from design information) to represent their combined shape.

Three points are required to fit a cylinder to match the profile of the pantograph. Using two points on the near beam 12a and a single point on the far beam 12b and given that the radius (r) is known. All the points on the same beam 12 lie on a circular slice on the surface of the cylinder (a plane normal to the axis). The direction of the axis of the cylinder ($\mathbf{n}$) is normal to any slice of the cylinder.

From Figures 19a and 19b the three points are $\mathbf{p}_1$ and $\mathbf{p}_2$ on one slice and $\mathbf{p}_3$ on the other slice.

The midpoint between $\mathbf{p}_1$ and $\mathbf{p}_2$ is: $p_{12} = \frac{1}{2}(p_1 + p_2)$ (Eqn 9)

The vector between $\mathbf{p}_1$ and $\mathbf{p}_2$ is: $m = (p_1 - p_2)$ (Eqn 10)

The distance between $\mathbf{p}_1$ and $\mathbf{p}_2$ is: d_{12} (Eqn 11)

The distance from the centre of the cylinder ($\mathbf{p}_c$) in this slice to $\mathbf{p}_{12}$ is:

$$h_{12} = \sqrt{r^2 - \left(\frac{d_{12}}{2}\right)^2} \quad \text{(Eqn 12)}$$

The plane that bisects $\mathbf{p}_1$ and $\mathbf{p}_2$ at $\mathbf{p}_{12}$ is: $\mathbf{m.w} = \mathbf{m.p}_{12}$ (Eqn 13)

The distance from $\mathbf{p}_3$ to this plane (from [Equation 13]) at $\mathbf{p'}_3$:

$$d_3 = \frac{m \cdot (p_{12} - p_3)}{|m|} \quad \text{(Eqn 14)}$$

The distance from the centre of the cylinder ($\mathbf{p'}_c$) in this slice to $\mathbf{p'}_3$ is:

$$h_3 = \sqrt{r^2 - d_3^{\,2}} \quad \text{(Eqn 15)}$$

The distance to project $\mathbf{p}_3$ onto the plane ("parallel plane") passing through $\mathbf{p}_1$ and $\mathbf{p}_2$ and parallel to the cylinder axis [Figure 20]: $h = h_3 - h_{12}$ (Eqn 16)

To determine the parallel plane (with normal $\mathbf{q}$), three points lying on it are required:

Point $\mathbf{p}_1$: $p_1 \cdot q = 1$ (Eqn 17)

Point $\mathbf{p}_2$: $p_2 \cdot q = 1$ (Eqn 18)

Point $\mathbf{p''}_3$ ($\mathbf{p}_3$ projected by distance h along normal $\mathbf{q}$):

$$\left(p_3 + \frac{h}{|q|}q\right) \cdot q = 1 \qquad \text{(Eqn 19)}$$

Solve [Equations 17, 18 and 19] simultaneously to solve for **q**, and then the cylinder axis direction (**n**) is: **n** = **q** x **m** (Eqn 20)

The **n** vector gives the pitch and yaw of the pantograph.

The co-ordinate transformation process produces a set of points along the front side of the carbon top edge ($\underline{c}_i$) and a set of points along the rear side of the carrier bottom edge ($\underline{b}_i$). Each corresponding pair of points (lying in the (y, z) plane) forms a vector ($\underline{v} = \underline{c} - \underline{b}$) [Figure 20]. To calculate the height of the carbon from the base of the carrier this vector must be represented in the pantograph co-ordinate system. The calibration co-ordinate system must be rotated by the pitch (θ), or equivalently, rotate the vector in the opposite direction by the pitch ($-\theta$).

Rotation about origin by θ:

$$\begin{bmatrix} y_p \\ z_p \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} y \\ z \end{bmatrix} \qquad \text{(Eqn 21)}$$

The height is the vertical component in pantograph co-ordinates:

$$h = z_p = y\sin\theta + z\cos\theta \qquad \text{(Eqn 22)}$$

Now that an embodiment of the present invention has been described in detail it will be apparent to those skilled in the relevant arts that numerous modifications and variations may be made without departing from the basic inventive concepts. In particular, the present embodiment is described in relation to a pantograph. However the invention is not limited to application to a pantograph and may be applied to other moving objects such as, for example a wheel of a train. The particular application required

will determine the number of fanned lasers and cameras required. If the present system is adapted to measure for example the tread thickness on a train wheel, a single fanned laser producing a laser stripe passing along a radius of the wheel is required.

Modifications and variations of the present invention which would be obvious to a person of ordinary skill in the art are deemed to be within the scope of the present invention the nature of which is to be determined from the above description.

Dated this 19th day of March 2004.

JRB ENGINEERING PTY LTD

By Its Patent Attorneys
GRIFFITH HACK

Fellows Institute of Patent and Trade Mark
Attorneys of Australia

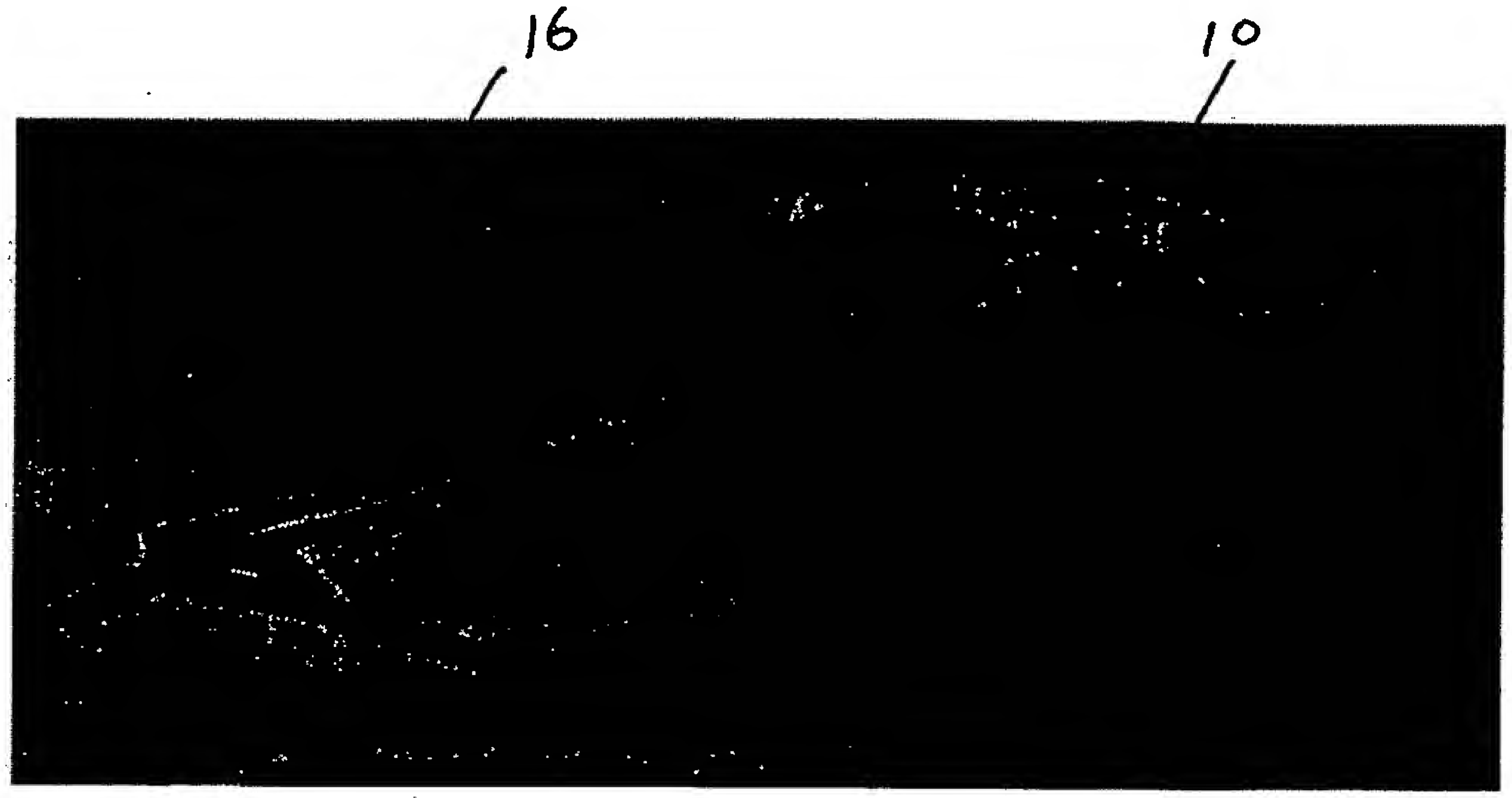


Fig 1

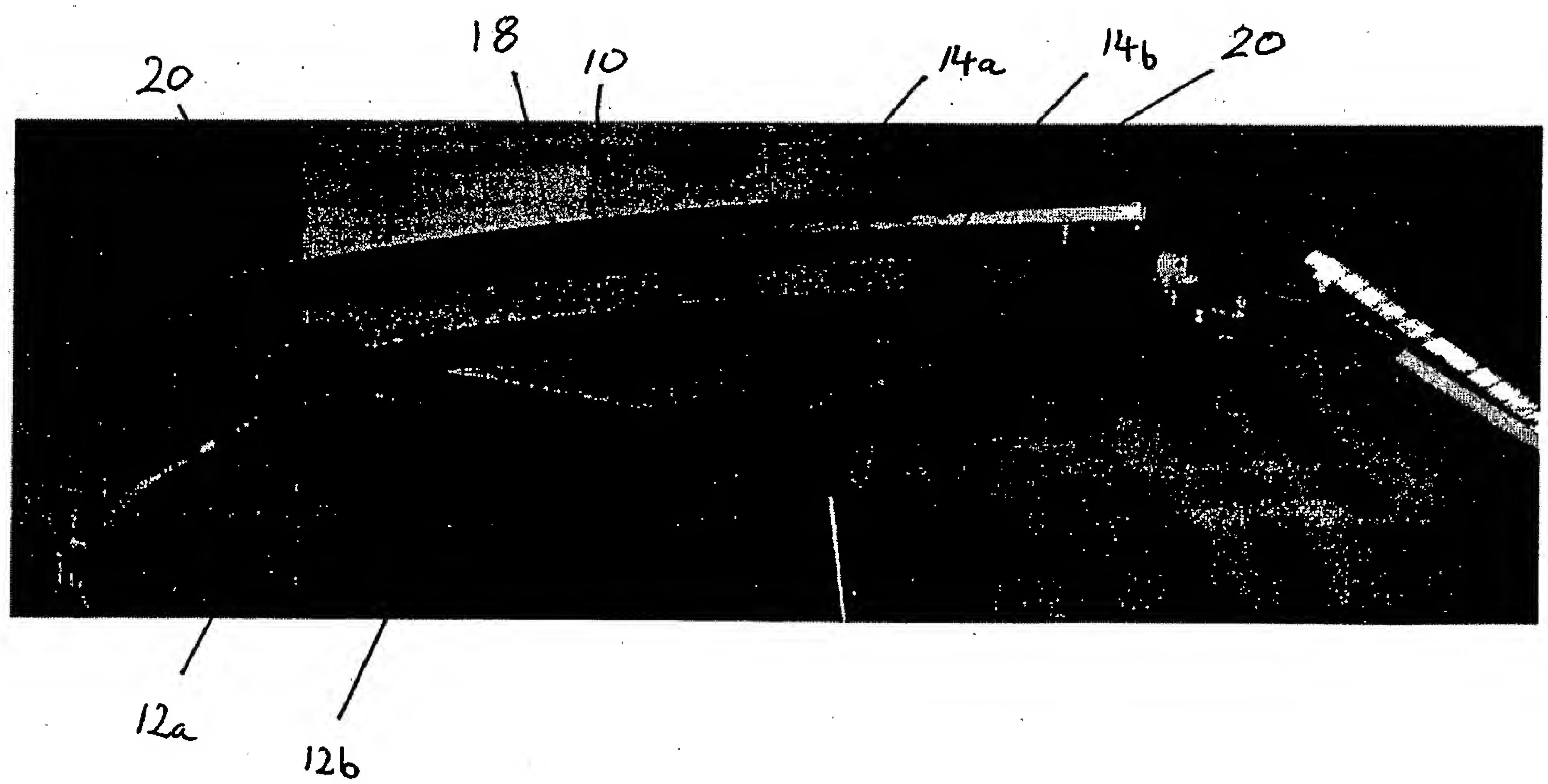


Fig 2

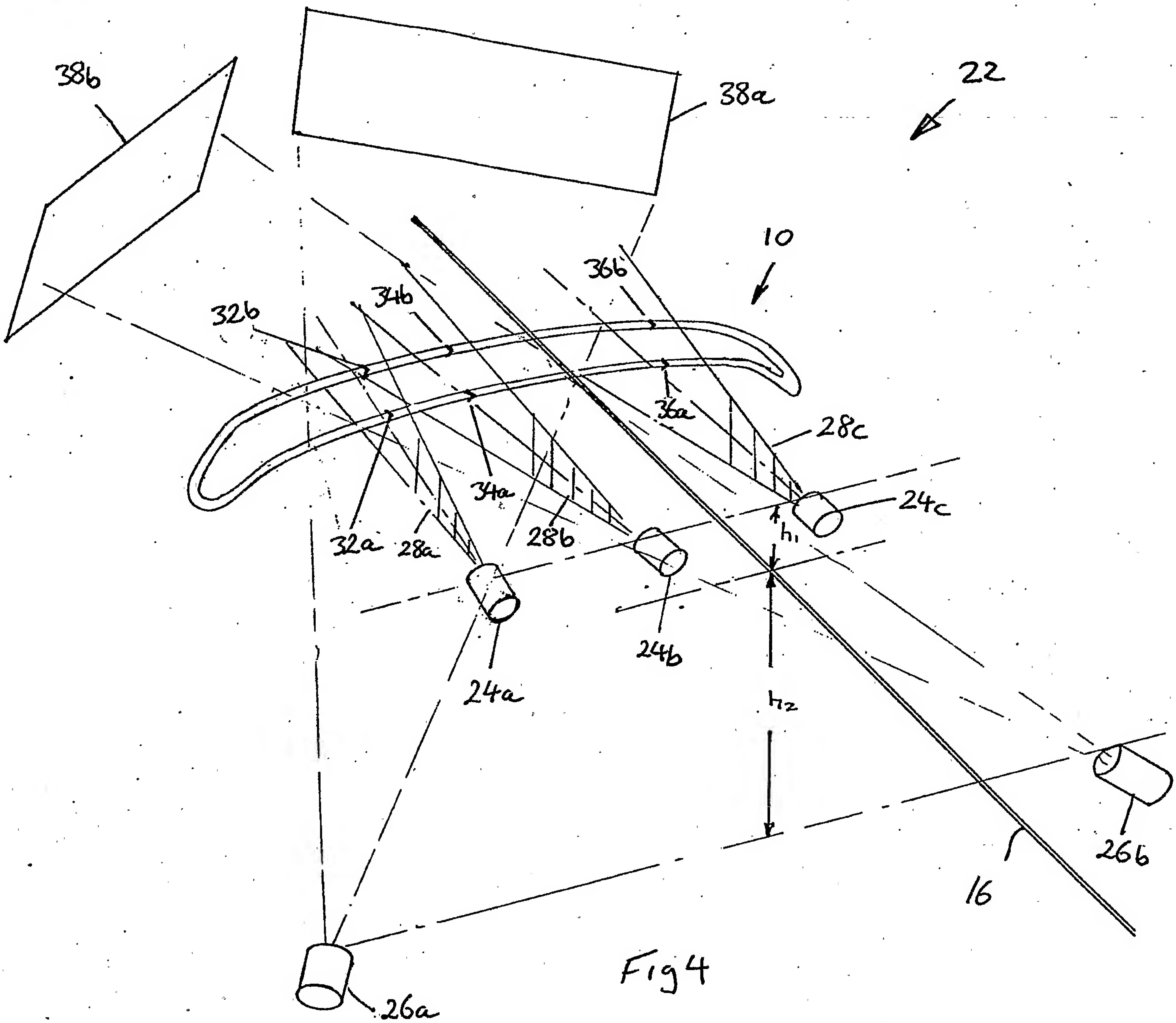


Fig 4

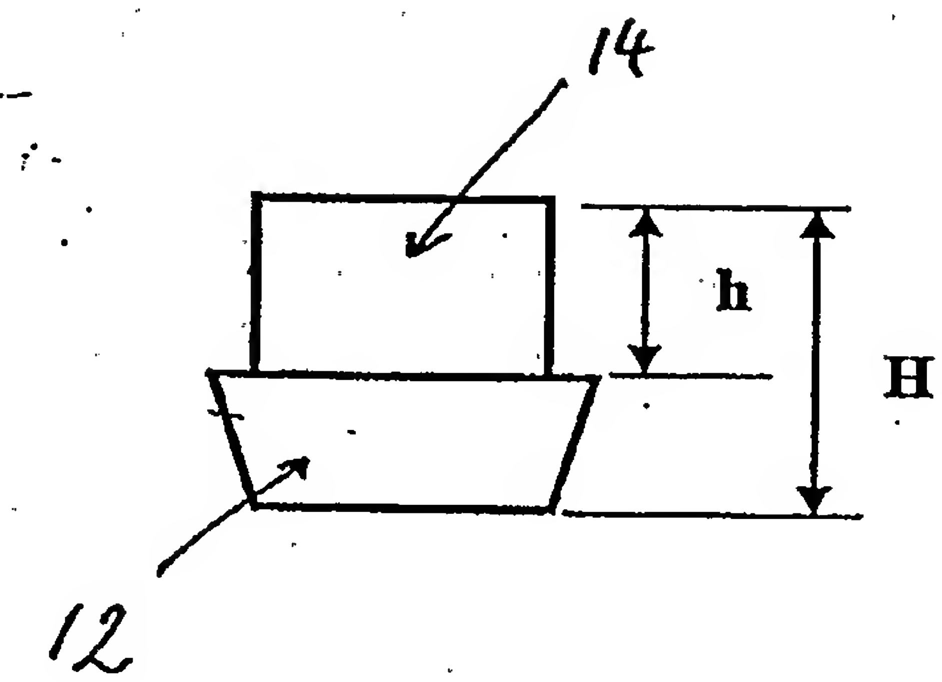


Figure 3

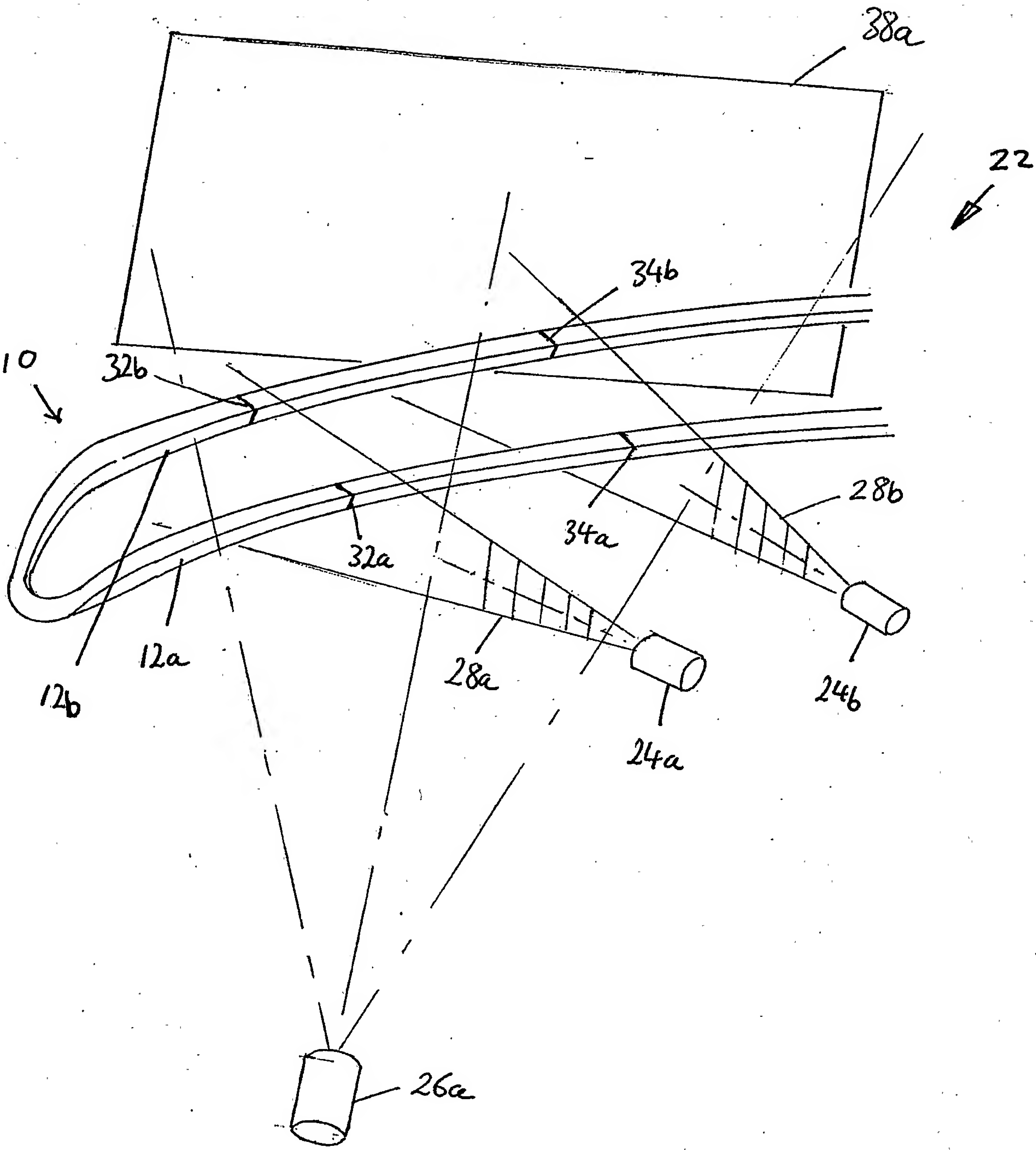


Fig 5

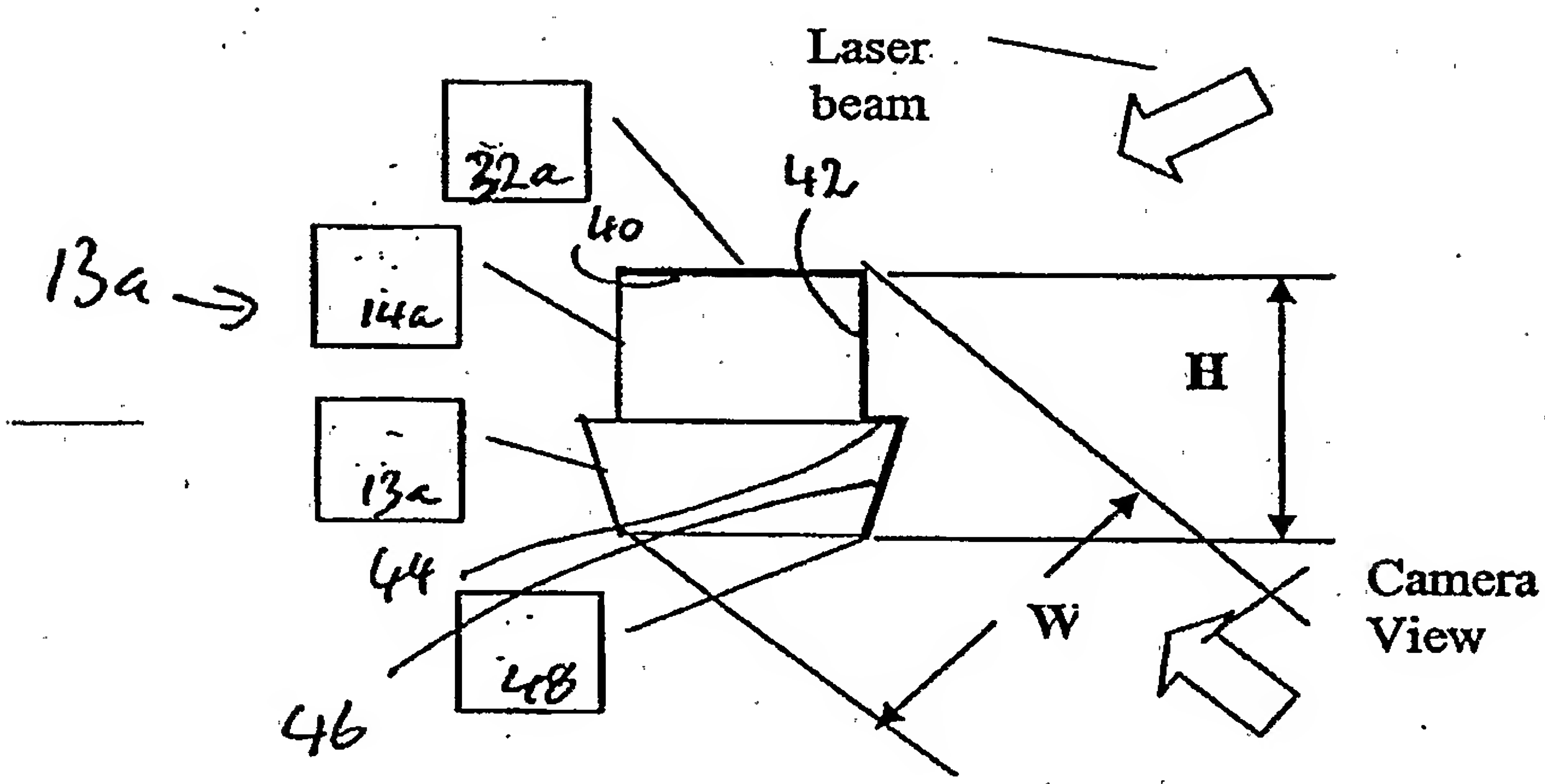


Figure 7

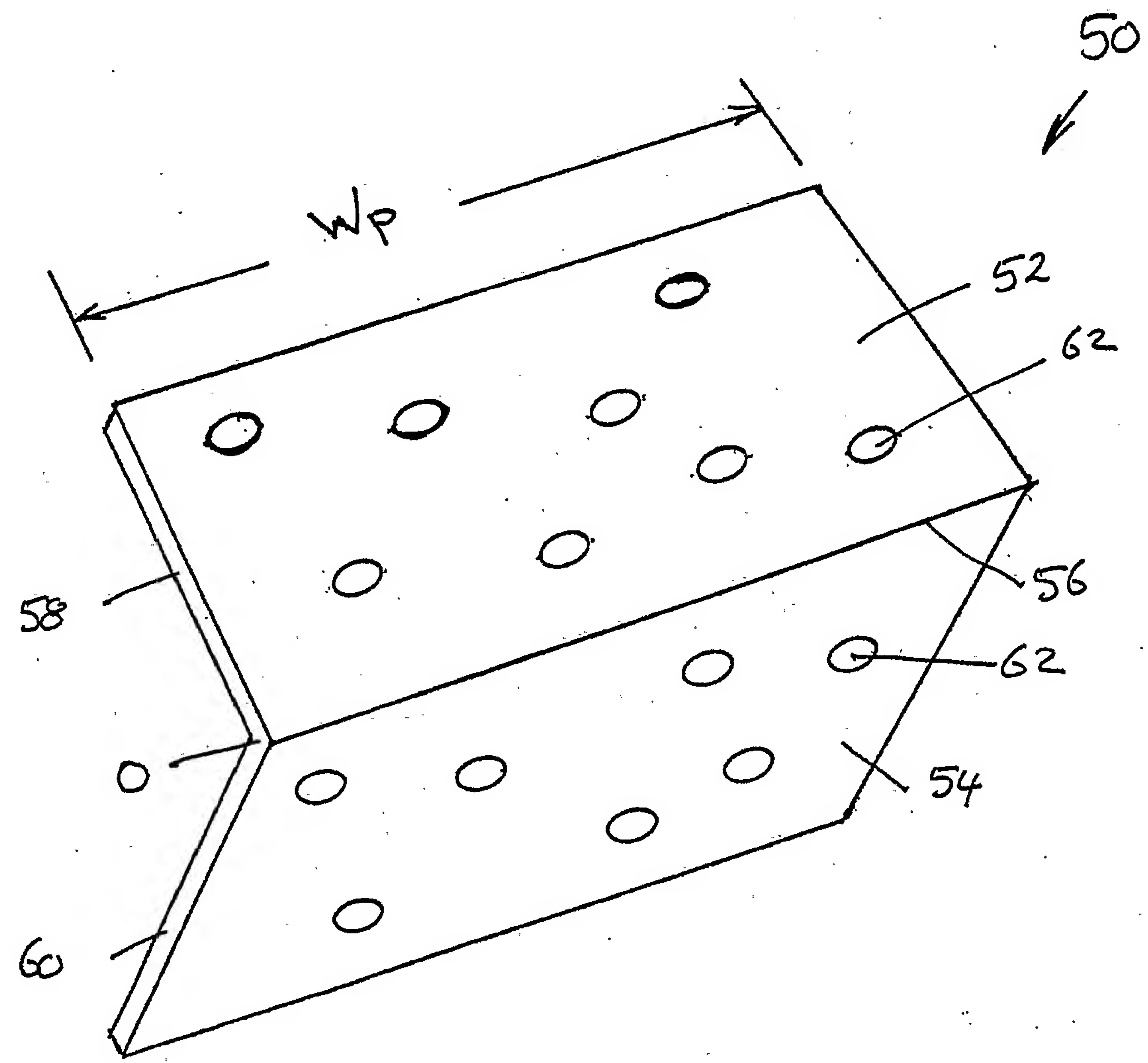


Fig 8

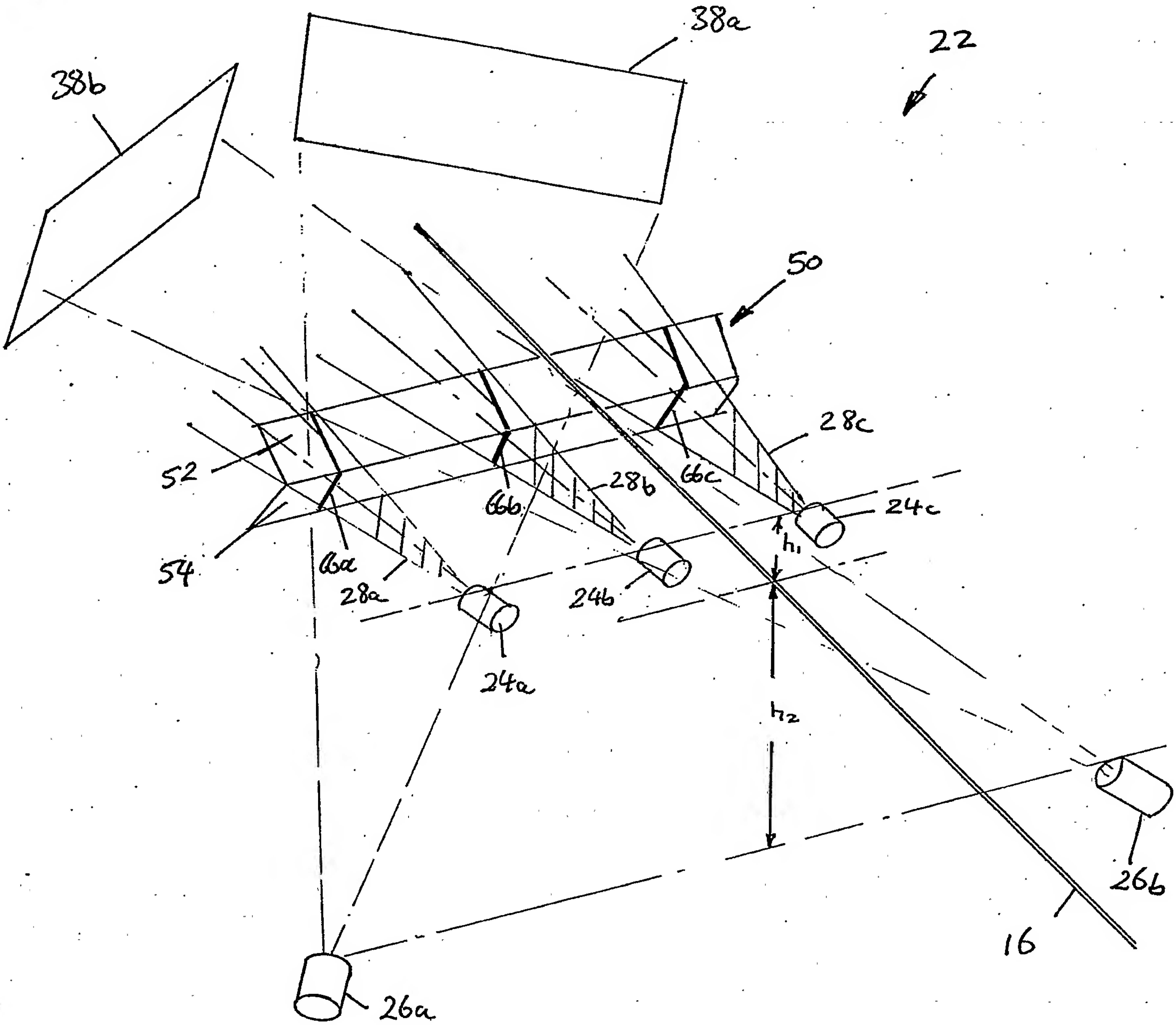

38a
38b
22
50
52
54
66a
66b
66c
28a
28b
28c
24a
24b
24c
h1
h2
26a
26b
16

Fig 9

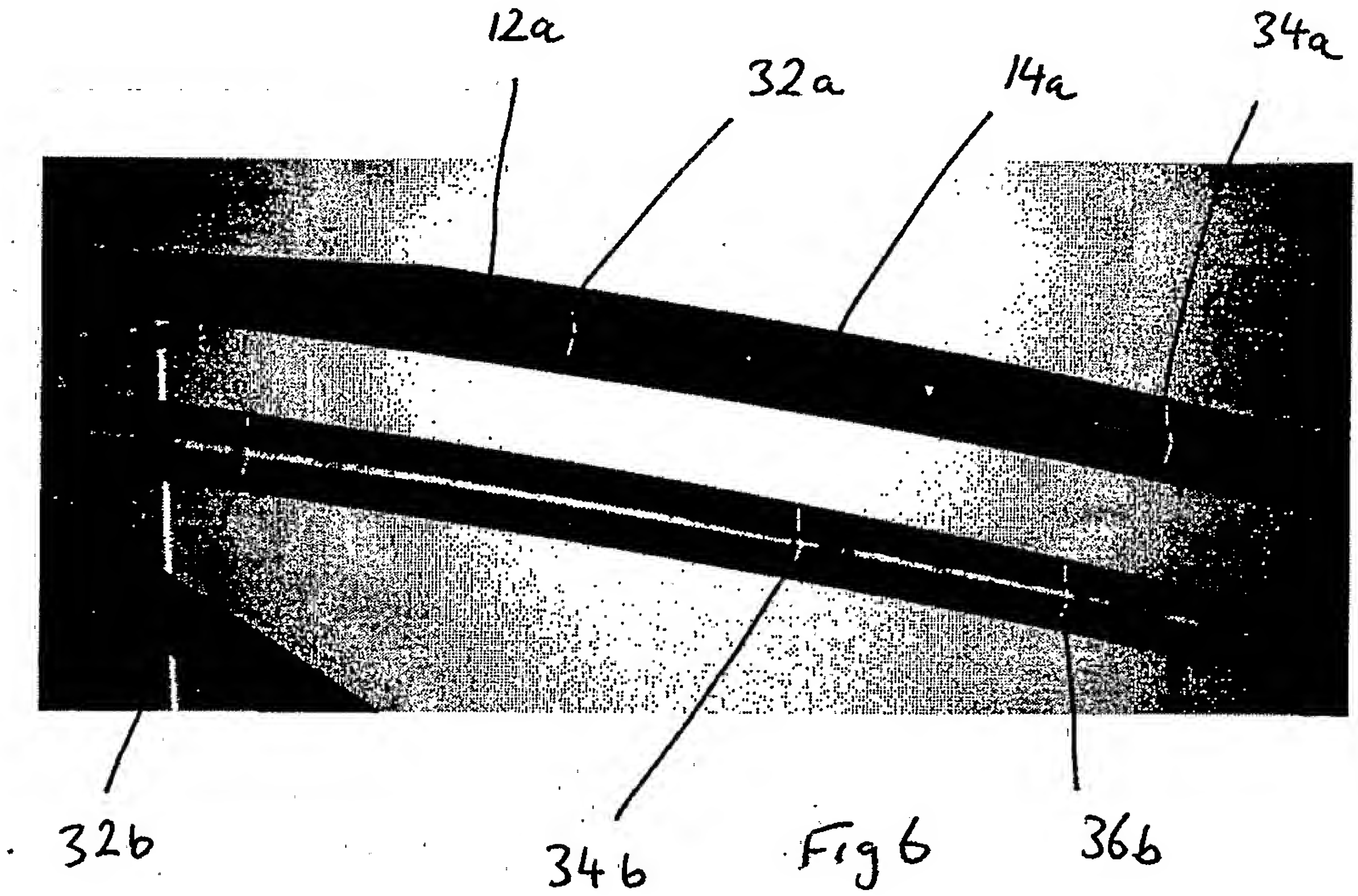


Fig 6

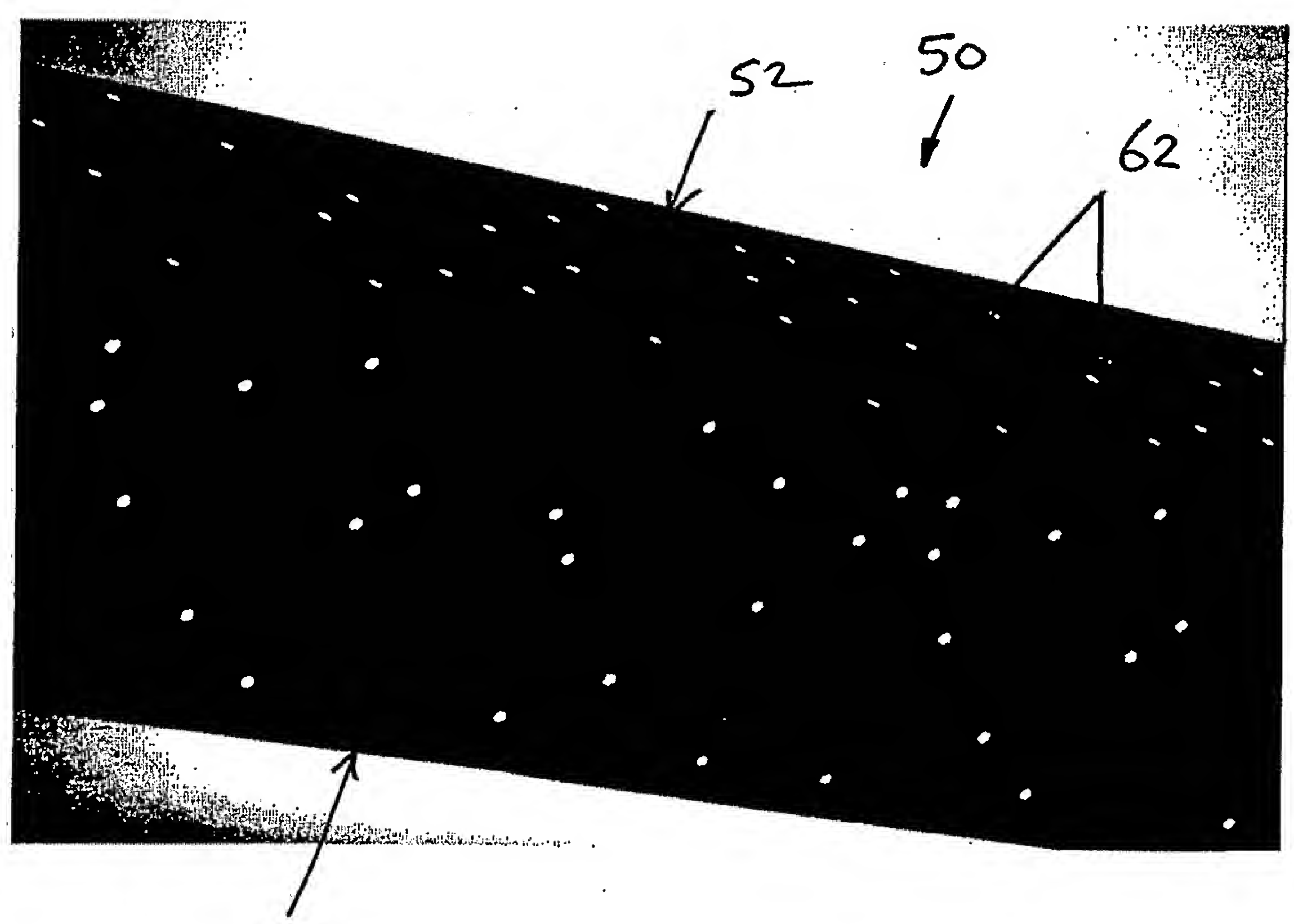


Fig 10

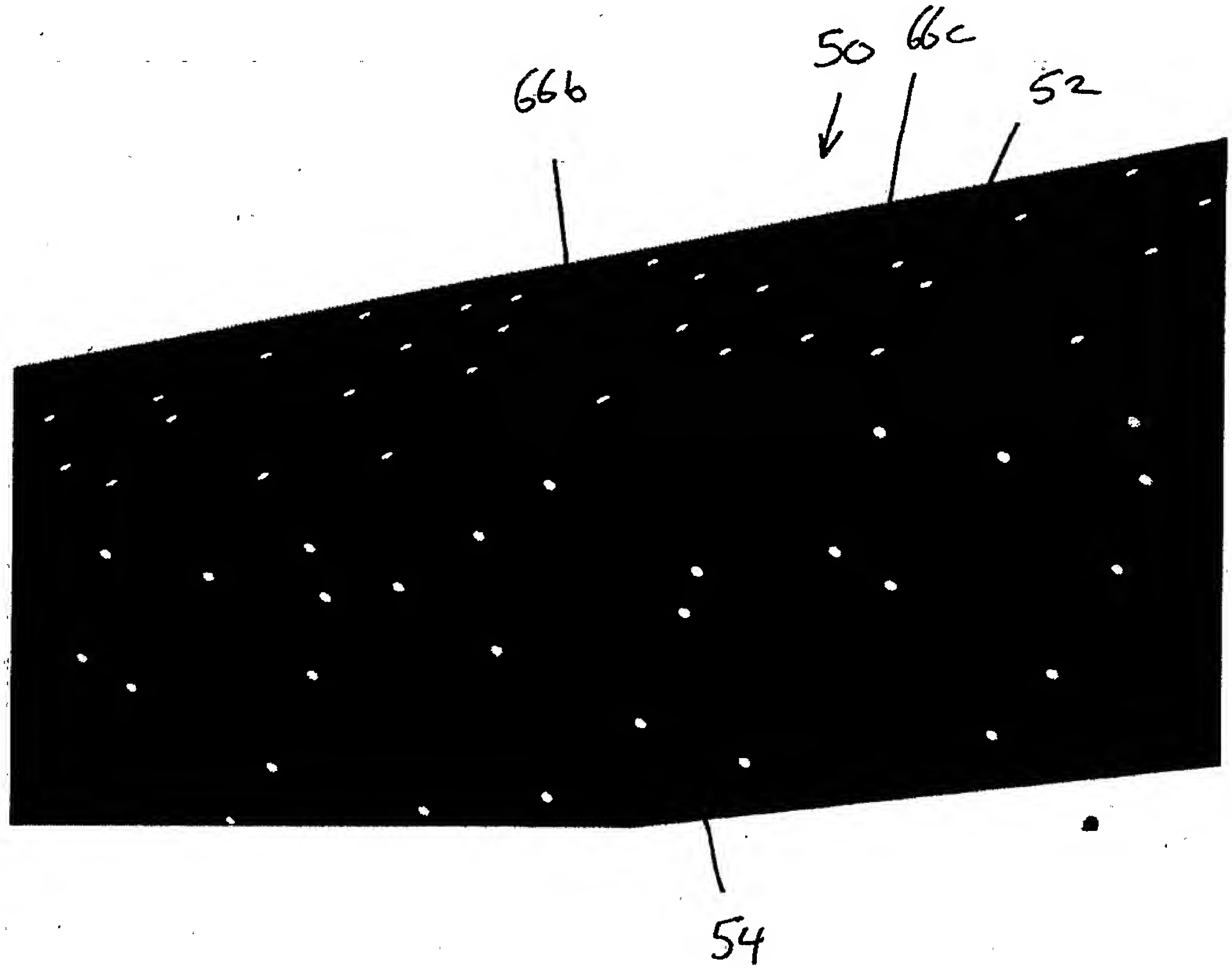


Fig 11

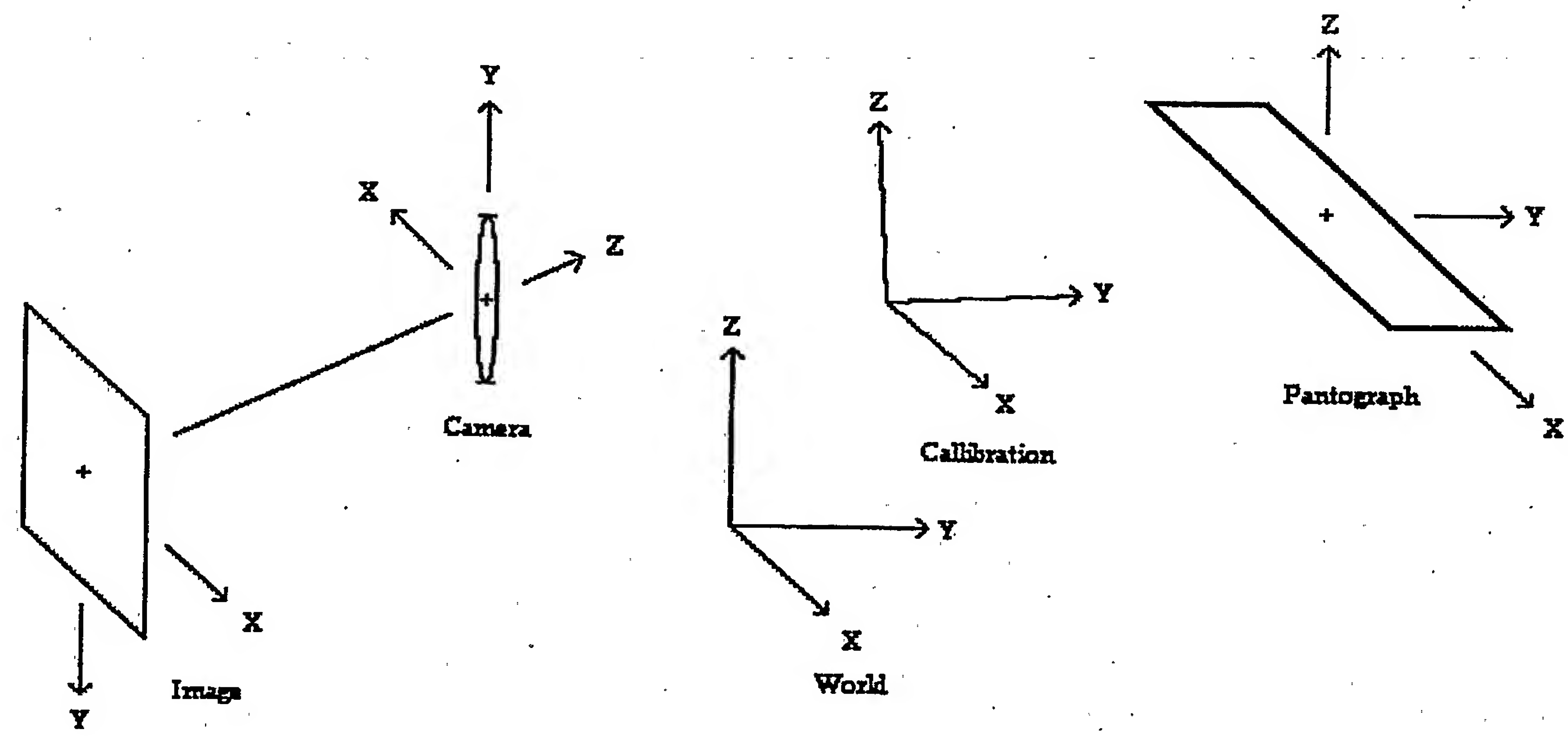


Figure 12: Reference Frames

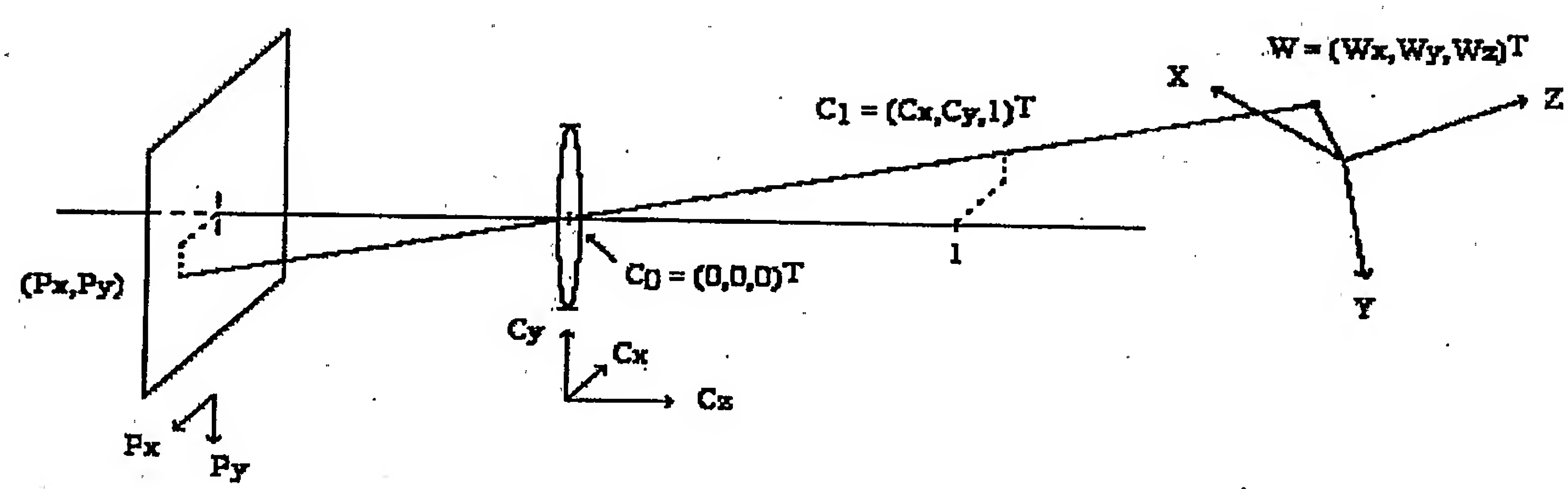


Figure 13: Coordinate Systems

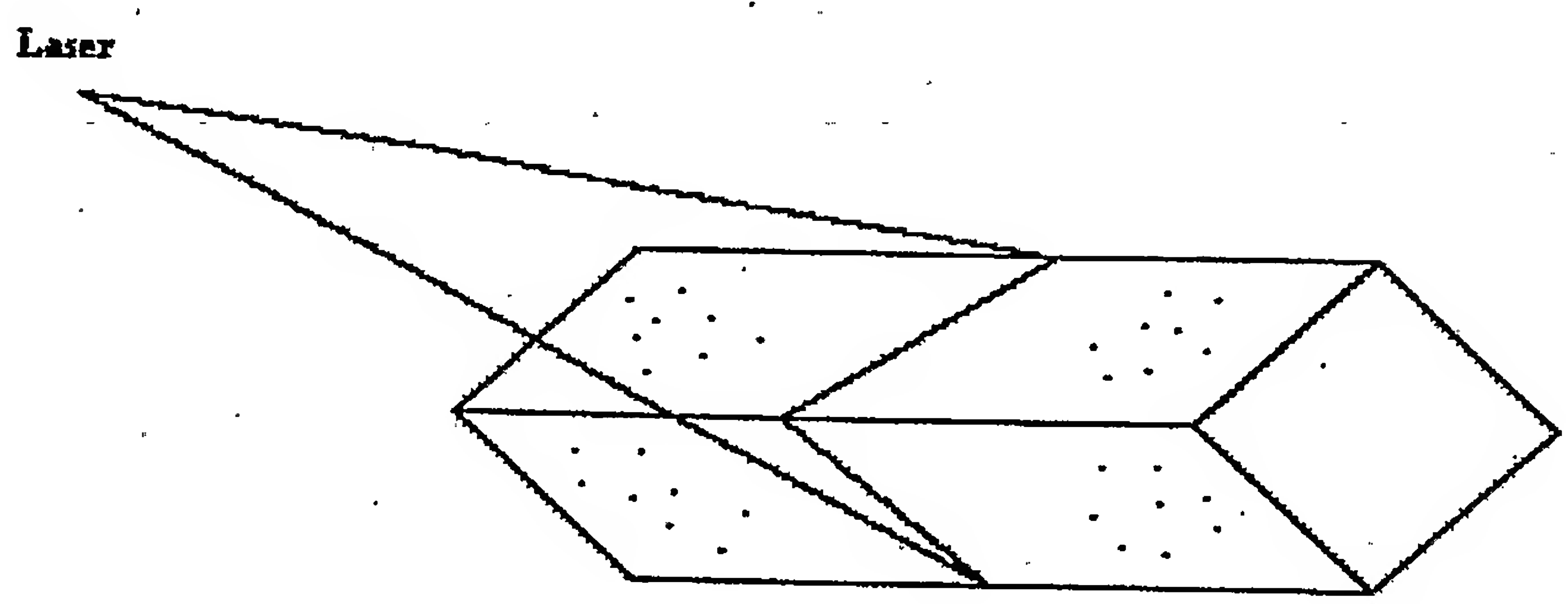


Figure 14: Calibration Block

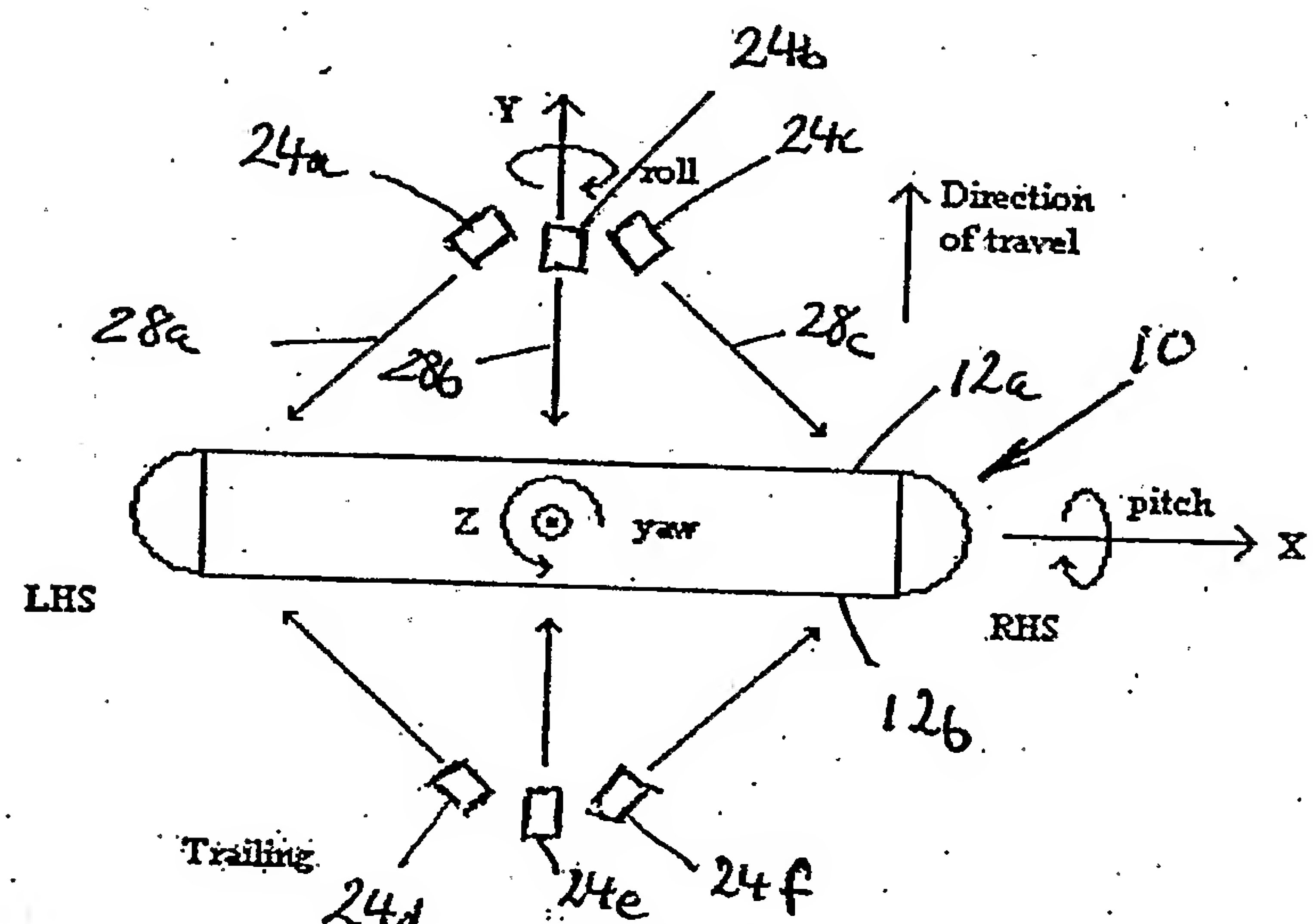


Figure 15

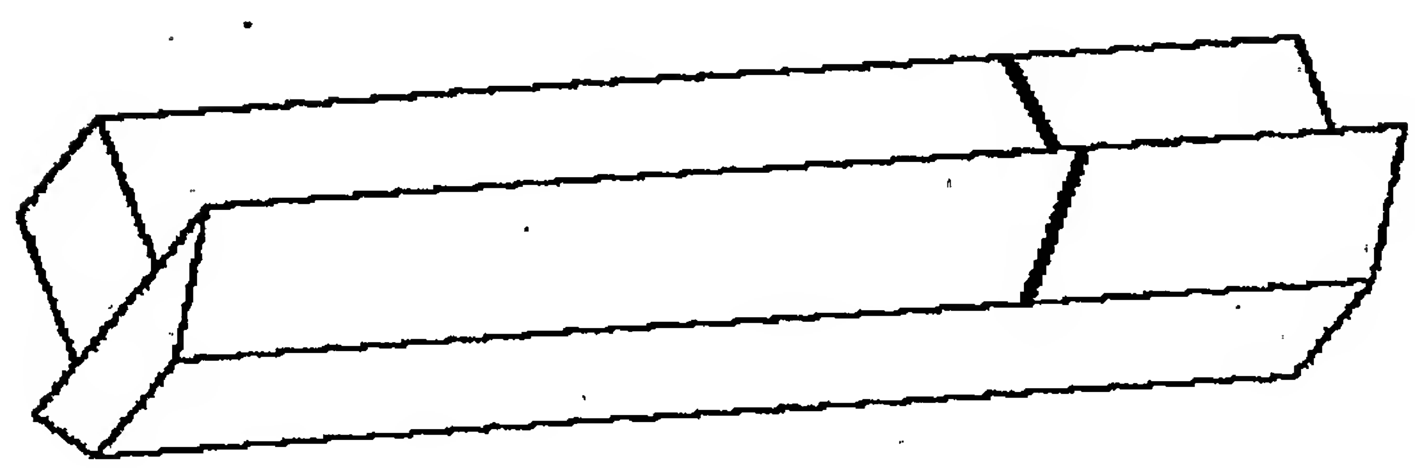


Figure 16: Stripe

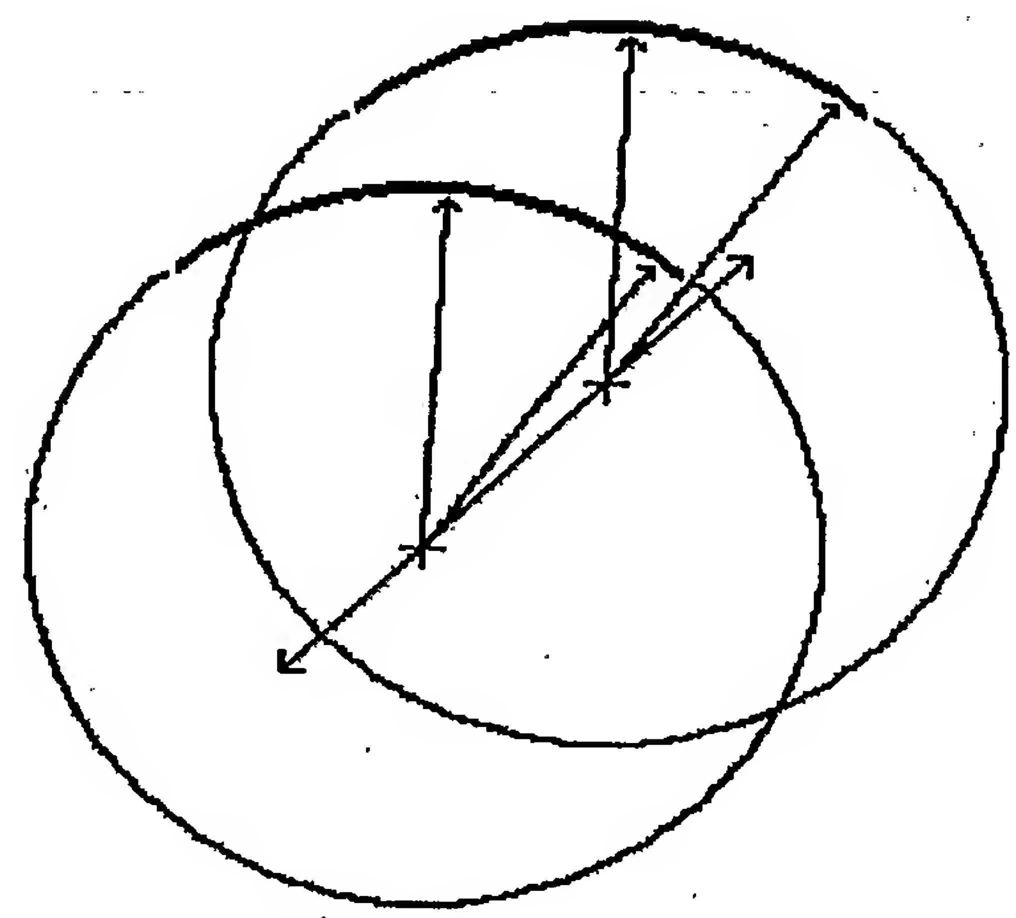


Figure 17: Fit Cylinder Profile

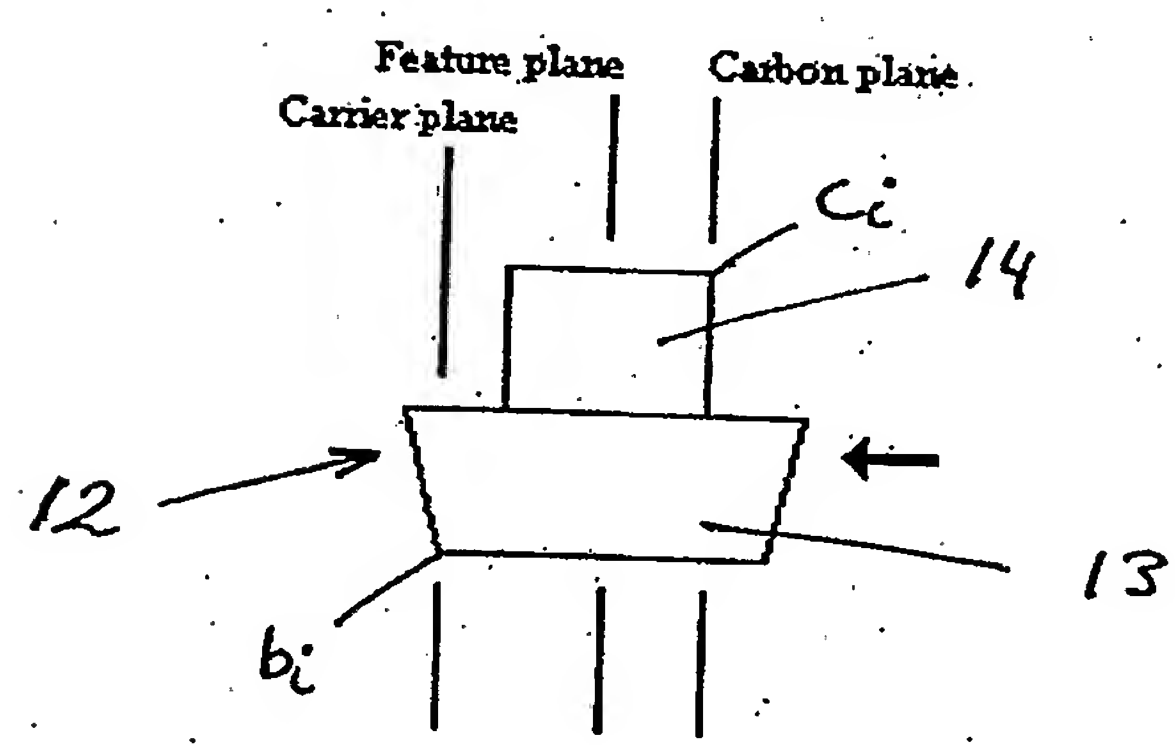


Figure 18

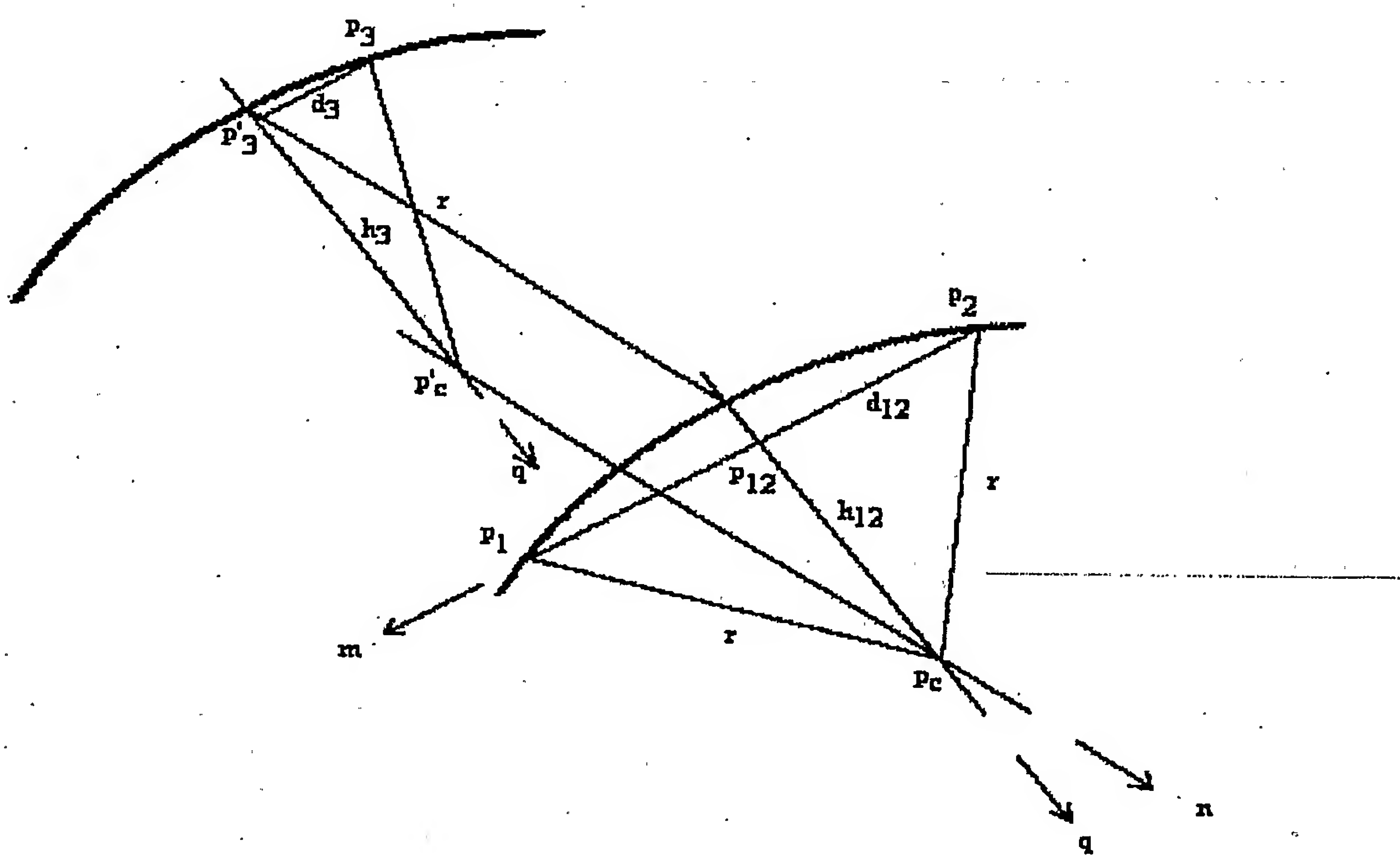
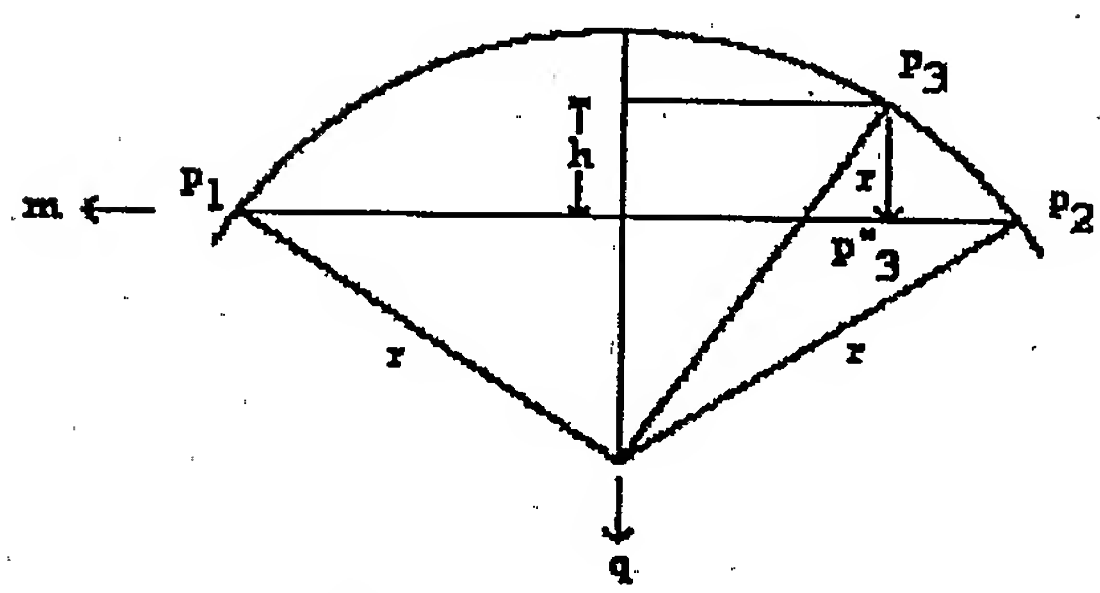


Figure ~~19~~: Fit Cylinder
19a



19b.
Figure ~~2~~: Cylinder View Along Axis

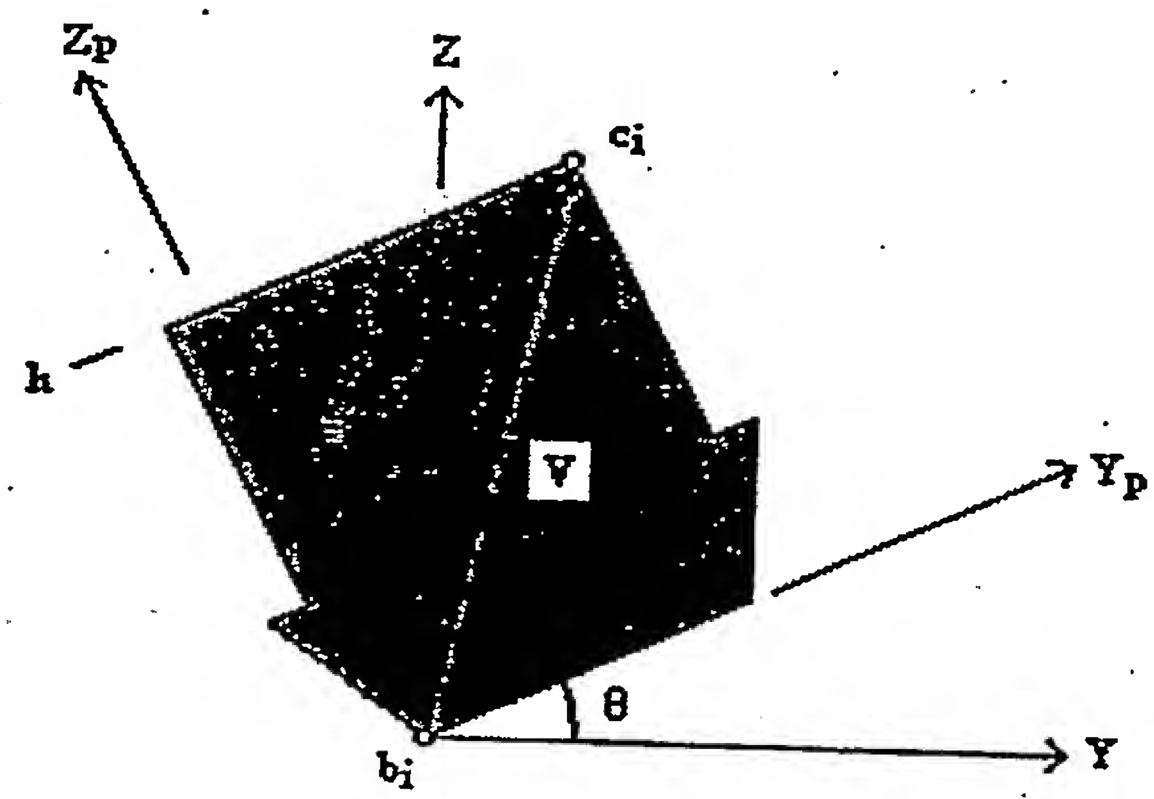


Figure 20